LCA Methodology with Case Studies

Integration of Life Cycle Assessment and Population Balance Model for Assessing Environmental Impacts of Product Population in a Social Scale

Case Studies for the Global Warming Potential of Air Conditioners in Japan

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DOI: http://dx.doi.org/10.1065/lca2003.04.112

Abstract

Scope. In this study, a dynamic model was built in which LCA and PBM were integrated to quantitatively assess the total environmental impacts induced by the product population in a society over time. Specifically, a determination was carried out concerning how Japan's air conditioner population is used (lifetime distribution, number of units, etc.) and an assessment was made concerning the Global Warming Potential (GWP) associated with the air conditioner population.

Methods. The proposed dynamic model was applied to air conditioners for analyzing the total GWP caused by the air conditioner population in Japan from 1990 to 2010. To create a trend forecast model for future environmental load, scenarios for air conditioner production up to 2010 were formulated and the total GWP from the air conditioner population was predicted. Conducted also were sensitivity analyses whose parameters were air conditioner performance, lifetime and the rate of refrigerant recovery when retired units are processed.

Results and Discussion. Applying the PBM to the air conditioner population in 2000, it was found that 81.5 million units consumed 5.94×10^{10} kWh in that year, which was a 6.1% increase in the total annual power consumption in 1990. In both a stationary scenario and a steady growth (1.5% annual increase), it was found that the total GWP would be 27.7% higher than in 1990 under the stationary scenario and 37.8% higher under the steady growth scenario. The improvements in air conditioner performance will have a small effect on reducing the total GWP from that population. Furthermore, in connection with the average lifetime, it was found that the GWP, due to refrigerant releases when units are disposed of, would be relatively large in 2000 and the following years.

Conclusions. Thus, shorter product lifetimes will spur a replacement of air conditioners with new units, a situation that will only lead to the reduction of GWP if the recovery rate of refrigerant is to be achieved to more than 50% under the stationary scenario.

Recommendations and Outlook. To meet COP3 targets for Japan in 2010 (i.e. to reach the same level as in 1990 for household appliances), our study shows that it will be vital to raise the refrigerant recovery rate. If the number of air conditioners in use remains unchanged, recovery would have to be 45.7%, but under the steady growth scenario it would have to be at least 60.4%. Therefore, it will be difficult to meet COP3 targets unless the refrigerant recovery rate is strongly increased. This method is applicable to assess not only the GWP of air conditioners, but also other environmental impacts caused by a variety of product populations, which will be quite effective for setting targets of products' performance, policymaking, etc.

Keywords: Air conditioner; COP3 target; global warming potential (GWP); life cycle assessment (LCA); lifetime shift; performance improvement; population balance model (PBM); scenario analysis; sensitivity analysis

Glossary

$C(x_t)$	average cooling/heating electricity consumption of air conditioners produced in each year (kWh/unit/yr)
E_{use}	total annual electricity consumption by entire air conditioner population (kWh/yr)
$E_{use}(x_t)$	annual electricity consumption by air conditioners produced in each year (kWh/yr)
$f(z)$	lifetime distribution [–]
G_{in}	production-stage greenhouse gas emissions (kg CO_2-eq./unit)
G_{out}	GWP of all air conditioners at the disposal stage (kg CO_2-eq./unit)
G_{pr}	greenhouse gas emissions per unit each year (kg CO_2-eq./unit)
GWP	Global Warming Potential
n_G	GWP of air conditioner refrigerant in a certain year (kg CO_2-eq.)
$N_{in}(x_t)$	number of air conditioners shipped each year (t) (unit/yr)
$N_{out}(x_t)$	number of air conditioners of a certain year (x_t) that are retired in each year (units/yr)
$N_{use}(x)$	number of air conditioners in use (units)
$P(x)$	survival probability of an air conditioner of a certain year of manufacture [–]
q_r	refrigerant recovery rate [–]
$W(x)$	mass of air conditioner refrigerant in a certain year (kg)
x_i	year under consideration
x_0	initial year of the years being analyzed (since 1965)
z	number of years in use (yr)

Introduction

Japan has actively worked to improve energy efficiency since the two oil shocks in the 1970s. Thanks to those efforts, final energy consumption in the industrial sector has tended to decrease as of late. On the other hand, consumption continues to grow in the household and transport sectors, and it is predicted to continue increasing at 1% to 2% a year [1]. Especially in the household sector, energy consumption has risen substantially in conjunction with the increase in consumer appliances and other items, so that this sector accounts for about 25% of total final energy consumption. Air conditioners account for 23.4% of household energy consumption, which is the highest percentage of all consumer appliances [2]. Hence, air conditioners are likely impose a heavier Global Warming Potential (GWP) than other products in the household. Yet, a product's environmental load arises not only while it is in use, but also when it is pro-

duced and disposed of. Life Cycle Assessment (LCA) is a technique that quantifies the environmental impacts caused by a product throughout its life cycle, and has been applied to air conditioners. Concerning the GWP of air conditioners, it has been shown that electricity consumption during usage is the predominant source, followed by refrigerant release in the disposal stage [3, 4, 5]. Accordingly, the most effective ways to mitigate the GWP of air conditioners include reducing air conditioner energy consumption, more efficient processing of refrigerant when units are retired, and switching to new refrigerants.

The characteristic of LCA is that it assesses environmental impacts on the basis of a product's functional unit [6]. Thus, LCA cannot be used to assess the environmental impacts produced by an entire product population in a society. In addition, there are usually lack of time aspects in LCA. LCA does not treat the effects on environmental impacts of products distributed in a society over time. With the introduction of time as an appropriate dimension to LCA, the influences of effects distributed over time can be more naturally and consistently treated [7].

Meanwhile, the Population Balance Model (PBM) is a way of ascertaining the total number of a product in use [8]. In PBM, the total number of a product in use in a particular year is calculated with the number of products made in the past and the lifetime distribution of the product. PBM deals with the time aspect of a product population in a society and, in some cases, product population in the future is predicted based on scenarios. There have been some case studies that have used the PBM to analyze the total number of products in use, their energy consumption and the magnitude of their environmental impacts. Hara et al. analyzed the energy consumption of refrigerator population using a mathematical model in Japan [9], and Kakudate et al. also investigated the usage and recycling pattern of steel in Japan [10].

LCA has life cycle perspective of a product. On the other hand, PBM has a time aspect and offers the total number of products in use. In this study, a dynamic model was built in which LCA and PBM were integrated to quantitatively assess the total environmental impacts induced by the product population in a society over time. This model will be quite effective for setting targets of products' performance, policymaking, etc. Specifically, the proposed dynamic model was applied to air conditioners for analyzing the total GWP caused by the production, use and disposal of the air conditioner population in Japan from 1990 to 2010. Scenarios were prepared for the air conditioners in use and for disposal up to 2010. Sensitivity analyses were performed to determine what a change in air conditioner performance, lifetime and refrigerant recovery rate will have on the GWP, and have identified the conditions necessary for meeting COP3 targets [11].

1 Methodology

Overview of the Model for Assessing Environmental Impacts of Products in a Social Scale

The following is an overview of the model developed in this study, in which LCA was integrated with PBM for assessing quantitatively environmental impacts of products in a social scale:

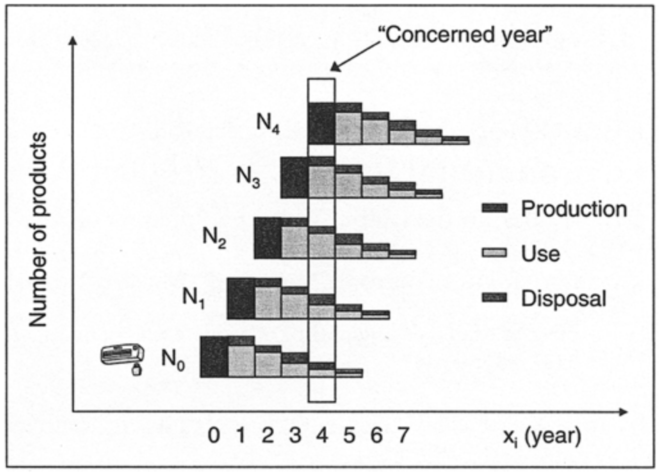

Fig. 1: Concept of PBM (N_x: number of air conditioners shipped in year (x) (unit/yr))

1) To use LCA to determine the environmental impacts of a single product at each stage of its life cycle (production, use and disposal).
2) To analyze PBM for the product in a society for determining the number of products that are produced, in use and disposed of in each year.

Fig. 1 illustrates the concept of using the PBM to determine the total number of a product in use.

In a certain year x_0, N_0 units of a product are produced and brought into use. The next year, x_1, some of the N_0 products are retired, and the rest continue to be used. In the meantime, also in year x_1, N_1 units of the product are produced and brought into use. In year x_2 more of the products made in year x_0 are retired and the rest continue to be used, while at the same time some of the N_1 products made in year x_1 are retired and the rest continue in service. Also in year x_2, N_2 new products are made and brought into use. In the next year (x_3), the following year (x_4), and subsequent years, the same thing happens so that the total number of products in use and disposed of in any particular year can be determined from the number of products made in that year and all past years, and the lifetime distribution of the product. In some cases, scenarios are further prepared for assessing the number of products in use in the future.

3) To calculate total environmental impacts of the product population in the society in each year, which consist of those caused by the production of new products, products in use and disposal. In this stage, LCA and PBM are integrated.
4) To perform a sensitivity analysis of the effects that changes in product performance, lifetime and the manner of disposal would have on the environmental impacts.

It is then possible to use the results for applications such as identifying product performance targets, requirements for meeting the societal goal.

2 Case Studies for Air Conditioners in Japan

In this study, the developed model was applied to air conditioners for quantitatively assessing the GWP of the air conditioner population in Japan. The procedures mentioned above were adopted. In analyzing PBM for air conditioners

in Japan, scenarios were prepared for assessing the number of air conditioners in use and their disposal up to 2010. Performed were sensitivity analyses of the effects that a change air conditioner performance, lifetime and refrigerant recovery rate would have on the GWP. It is then possible to use the results for applications such as identifying what must be done to meet COP3 targets. The COP3 targets for Japan is to reduce Green House Gas (GHG) emissions (CO_2 equiv.) by 6% compared with those in 1990 at a national level [11]. Allocation of the GHG emission reduction in each sector is now being discussed and not so clear for home appliances. So, the authors assumed the COP3 target for home appliances is to reach the same level as in 1990.

2.1 LCA of individual air conditioners

To calculate the GWP of a single air conditioner at each stage of its life cycle (production, use, and disposal), data were collected from an existing LCA case study for an air conditioner [3]. According to the literature, raw material production, parts assembly and transport produce only about 3% of a unit's GWP, while the product's use causes the overwhelming majority at 78%, followed by the refrigerant release at the disposal stage at 19% of the GWP [3]. The representative air conditioner was the split type (2.8-kW cooling capacity class) generally used in residences. GWP from manufacturing one air conditioner (G_{pr}) was 88.4 kg CO_2-eq./unit. While this value is not necessarily representative of the GWP from manufacturing an air conditioner during all years, this value was used for all air conditioners in consideration of the fact that the GWP from manufacturing is small in comparison with the emissions over a product's entire life cycle.

The GWP from the use of an air conditioner can be determined by multiplying the average electricity consumption of air conditioners produced in each year by the GWP intensity of the electricity [12]. From statistics and interviews with manufacturers, surveyed was the cooling/heating electricity consumption C(x) (kWh/unit/yr) of 2.8-kW air conditioners made in 1990 or later (**Fig. 2**).

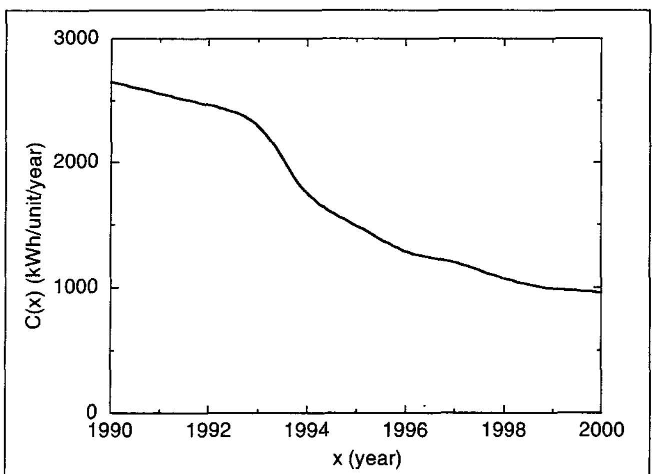

Fig. 2: Annual energy consumption of air conditioners of the 2.8-kW cooling capacity class in Japan

C(x) gives an index of air conditioner performance for each year of manufacture, and is determined by assuming use in a typical home (timber construction, facing south, Western-style) with space cooling at 300K, space heating at 293K, cooling for 3.6 months/yr, heating for 5.5 months/yr and operation of 18 h/d [13]. In 1990 and following years, seasonal cooling/heating electricity consumption fell dramatically owing to the introduction of inverter control and brushless motors, but control systems have recently reached about the highest efficiency possible, making for little further change.

On the basis of interviews with manufacturers, it was assumed that the refrigerant used in air conditioners was HCFC-R22 until 1998, but HFC-R410-A in 1999 and thereafter, which used amounts of those specific refrigerants per unit of 0.8 and 1.2 kg, respectively. Japan's Law for the Recycling of Specified Kinds of Home Appliances (Appliance Recycling Law) stipulates that when an air conditioner is retired, its materials must be recycled and its refrigerant recovered [14]. Before the Appliance Recycling Law, most of the refrigerant was likely to be released into the atmosphere, due to the insufficiency of recycling plants and recovery equipment. For this reason, it was assumed that all of the refrigerants used in air conditioners are released into the atmosphere at the disposal stage. In this work, GWP_{100} factors were used to characterize all greenhouse gases [15].

2.2 Analyses of the PBM for air conditioners in Japan

The PBM was adopted to find the total number of air conditioners produced, in use and disposed of in Japan for each year. In this study, a simplified model is based on air conditioners with a 2.8-kW cooling capacity, which makes up the largest portion of the population and offers the best statistical data. The validity of this simplified model was checked and compared with the results obtained by another model using several air conditioners capacities (2.2, 2.5, 2.8, and 4.0 kW), which are described in the **Appendix**.

The production of 2.8-kW split-type air conditioners according to year, N_{in} (units/yr), was determined from statistical data [16]. Although there were production spikes in 1991 and 1996 owing to very hot weather, production rose smoothly overall and has recently stabilized at somewhat above 8 million units per year. The total number of air conditioners in use, N_{use} (units), was calculated in the manner below by using the number of units produced each year, $N_{in}(x_t)$ (units/yr) and the probability of an air conditioner's surviving in service, $P(x_t)$.

In year x_i, the survival probability $P(x_t)$ of an air conditioner made in year x_t ($x_i > x_t$) is given by Eq. (1), when employing the air conditioner lifetime distribution function f(t). Here, z is the number of years in use: $z = x_i - x_t$.

$$P(x_t) = \left(1 - \int_0^z f(t)dt\right) \tag{1}$$

Hence, in year x_i, the number of air conditioners surviving when produced in year x_t, $N_{use}(x_t)$ (units), is the product of

the survival probability $P(x_t)$ and the number of air conditioners produced in year x_t, $N_{in}(x_t)$. (Eq. (2))

$$N_{use}(x_t) = N_{in}(x_t)\left(1 - \int_0^z f(t)dt\right) \tag{2}$$

The lifetime distribution of air conditioners in use was determined from statistical data on the number of years used and the disposal rate [17]. The gamma distribution function in Eqs. (3) and (4) produces an excellent approximation to actual data for lifetime distribution (**Fig.** 3) [18].

$$f(x) = \frac{\lambda^{\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-\lambda x} \tag{3}$$

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx \tag{4}$$

where $x \geq 0$, α, and λ (>0) are coefficients.

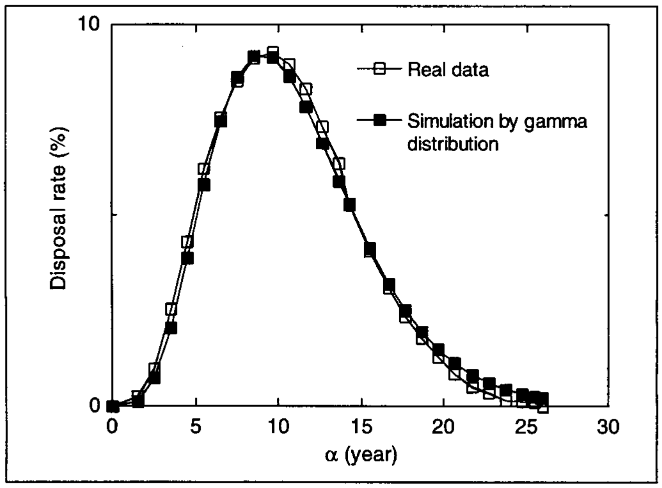

Fig. 3: Average lifetime distribution of all air conditioners (from statistical data; curve fitting by gamma distribution). See Eqs. 3 and 4 for α

From Eqs. (1) through (4), the number of air conditioners in use up to 2000 was estimated (**Fig. 4**).

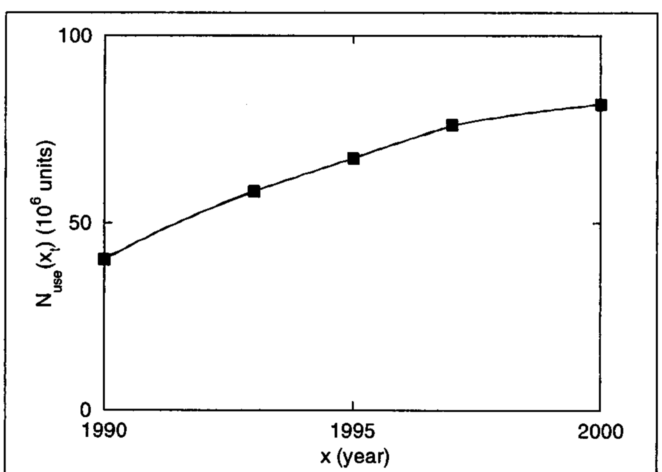

Fig. 4: Total number of air conditioners in use in Japan during 1990–2000

With the increase in the number of air conditioners produced, the number of units in use also increased, making for an estimated 81.5 million units in use in 2000. This number is not far removed from the 88.62 million units estimated from per-household ownership in 1998, which was obtained from statistical data [19].

2.3 Calculating GWP from the air conditioner population

2.3.1 Calculating GWP from air conditioners at the manufacturing stage

The amount of GWP at the manufacturing stage, G_{in} (kg CO_2/yr), is the contribution of the air conditioner population newly produced and brought into use in the year x_i. If the GHG emissions of one unit in year x_i are $G_{pr}(x_i)$ (kg CO_2-eq./unit), they are given by Eq. (5):

$$G_{in} = G_{pr}(x_i) \times N_{in}(x_i) \tag{5}$$

where $N_{in}(x_i)$ is the number of air conditioners produced and brought into use in year x_i.

2.3.2 Calculating seasonal cooling/heating electricity consumption and GWP

The seasonal cooling/heating electricity consumption of the air conditioners produced in year x_t surviving in year x_i, $E_{use}(x_t)$, is determined by the product of the number of surviving units, $N_{use}(x_t)$ and the performance, i.e. the seasonal cooling/heating electricity consumption of the units produced in year x_t, $C(x_t)$. Additionally, the number of surviving units, $N_{use}(x_t)$ is determined from the number of units shipped in each year, $N_{in}(x_t)$ (units/yr), and the survival probability, $P(x_t)$, in year x_i (Eq. 6).

$$\begin{aligned} E_{use}(x_t) &= C(x_t)N_{use}(x_t) \\ &= C(x_t)N_{in}(x_t)P(x_t) \\ &= C(x_t)N_{in}(x_t)\left(1 - \int_0^z f(t)dt\right) \end{aligned} \tag{6}$$

With the electricity consumption of air conditioners made in year x_t, $E_{use}(x_t)$, the seasonal cooling/heating electricity consumption of the entire air conditioner population in use, E_{use}, is defined by Eq. (7):

$$E_{use} = \int_{x_0}^{x_i} C(x)N_{in}(x)\left(1 - \int_0^z f(t)dt\right)dx \tag{7}$$

where $z = x_i - x_t$, and x_0 is the initial year of the years being analyzed.

Fig. 5 shows the results obtained when using the PBM to find the usage-stage seasonal cooling/heating electricity consumption of air conditioners up to 2000, $E_{use}(x_t)$.

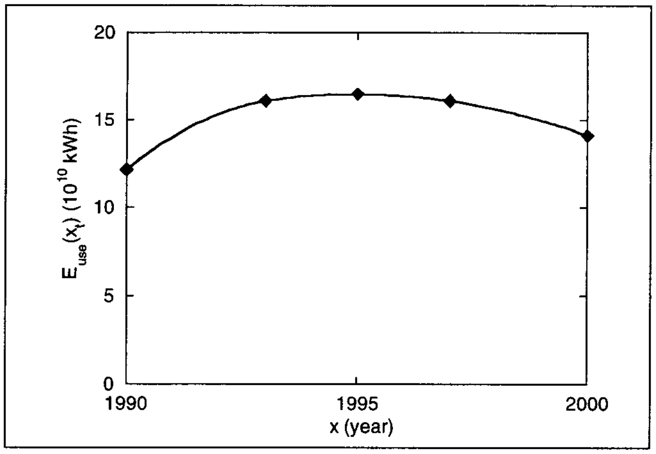

Fig. 5: Total electricity consumption by air conditioners in use in Japan during 1990–2000 (assuming that year-round space heating and cooling needs are all met by air conditioners)

There has been a steep growth in annual electricity consumption as the number of air conditioners has increased. Usage-stage electricity consumption rose in 1990 and thereafter, peaked in 1995, and has since declined. Usage-stage seasonal cooling/heating electricity consumption in 2000 was 14.22×10^{10} kWh according to Eq. (7), but this value was very large in comparison with the actual electricity consumption of 5.94×10^{10} kWh [20]. The reason is that this model assumes that year-round space heating and cooling needs are all met by air conditioners. In fact, kerosene stove and gas space heaters meet the larger proportion of space heating needs [20]. Thus, with 2000 as the base year, the seasonal cooling/heating electricity consumption was reevaluated by using the correction coefficient, k (0.42), to produce a value close to actual energy consumption. As a result, seasonal cooling/heating electricity consumption came to 6.89×10^{10} kWh in 1995 and 5.94×10^{10} kWh in 2000, and it was estimated that 2000 consumption was about 6.1% higher than that in 1990.

The seasonal cooling/heating electricity consumption of the entire air conditioner population in use was multiplied by the GWP intensity of the electricity consumed (0.45 kg-CO_2 equiv./kWh) [12] to calculate the total GWP of the entire air conditioner population in use.

2.3.3 Calculating GWP of air conditioners at the disposal stage

GWP of the air conditioner population at the disposal stage, G_{out} (kg CO_2), are the product of the GWP of the various refrigerants, $n_G(x_t)$ (kg CO_2 equiv./kg), the amount of the refrigerants, $W(x_t)$ (kg), and the refrigerant recovery rate, q_r (Eq. 8), assuming that in year x_i the number of air conditioners of a certain year (x_t) that are retired in accordance with the lifetime distribution f(t) is $N_{out}(x_t)$ (units) (Eq. 9):

$$G_{out} = \int_{x_0}^{x_i} n_G(x_t)(1-q_r)W(x_t)N_{out}(x_t)dx_t \qquad (8)$$

$$N_{out}(x_t) = N_{in}\int_{z-1}^{z} f(t)dt \qquad (9)$$

where $z = x_i - x_t$, and x_0 is the initial year of the years being analyzed.

3 Results and Discussion

3.1 GWP of air conditioner population up to 2000

Fig. 6 shows the results obtained for the GWP caused by air conditioners up to 2000, taking into account their life cycle from production to disposal.

It is clear that the GWP due to air conditioners' electricity consumption in use is relatively large compared with other stages. The GWP due to air conditioner use peaked in 1995 and then declined in line with the seasonal cooling/heating electricity consumption $E_{use}(x_t)$ shown in Fig. 5. At the same time, more air conditioners are retired because more are produced, resulting in an increase in the contribution of GWP owing to the release of refrigerant at the disposal stage. Specifically, over the decade from 1990, GWP at the disposal stage increased about 4.9-fold from 0.24×10^{10} (kg CO_2 equiv.) to 1.18×10^{10} (kg CO_2 equiv.), making the total GWP amount 3.83×10^{10} (kg CO_2 equiv.) in 2000, a 52.0% increase as compared with 1990. It is evident from the foregoing that the refrigerant recovery in air conditioner disposal will be crucial because the amount of air conditioner disposal will rapidly increase.

Then, stationary and steady growth scenarios were prepared for air conditioner input, and predicted GWP under both scenarios.

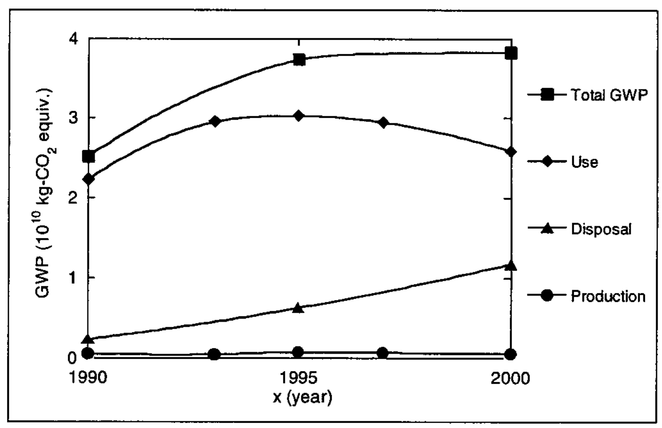

Fig. 6: GWP by all air conditioners in Japan during 1990–2000

3.2 Scenario-based analysis of GWP

As for two scenarios of the seasonal cooling/heating electricity consumption of Japan's total air conditioner population in 2010: 1) a stationary scenario, in which the number of units in use remains the same according to a medium-term demand forecast [21], and 2) a steady growth scenario, in which the penetration rate of air conditioners increases, so that penetration will have risen from the current 84.6% to 100% in 2010. These scenarios were used in a sensitivity analysis.

Units in use under the stationary scenario will stay at the 83.9 million mark beyond 2000, but, under the steady growth scenario, it was calculated that the number would continue to increase steadily, rising to 94.6 million in 2010. In particular, the number in use under the steady growth scenario corresponds with a sound forecast in view of the electric

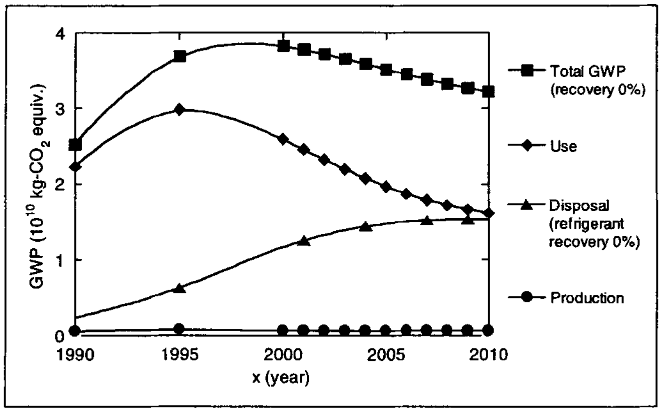

Fig. 7: GWP of all air conditioners in Japan during 1990–2010 according to stationary scenario

energy sales forecast and power plant setting plan of the Federation of Electric Power Companies in Japan [22].

Assuming the refrigerant recovery rate to be 0%, the GWP was determined up to 2010 under the stationary scenario (**Fig.** 7).

Although the total GWP tended to increase until 2000, they gradually declined after that. The production stage accounts for a mere 1.7% to 2.0% of the total GWP; use-stage GWP peaked in 1995, and declined thereafter. On the other hand, disposal-stage GWP from refrigerant increased because even in 2000 and the following years many of the air conditioners brought into use during the 1990s were scrapped. Improvements in air conditioner performance will bring down use-stage GWP, making them 1.81×10^{10} kg CO_2 equiv. in 2010. Meanwhile, disposal-stage GWP in 2010 will be 1.58×10^{10} kg CO_2 equiv., about the same as use-stage GWP. In 2010, the total GWP by all air conditioners in Japan will be 27.7% higher compared with that in 2000.

3.3 Sensitivity Analysis

3.3.1 Factors considered in the sensitivity analysis

Sensitivity analyses were conducted of the GWP of air conditioners in Japan while changing air conditioner performance, average lifetime and refrigerant recovery rate. As was shown in Fig. 2, air conditioner performance improved every year in the first half of the 1990s, as seen in the substantial drop in seasonal cooling/heating electricity consumption, but there has been no significant improvement recently. For that reason, a rate of improvement at 3.0%/yr was set for 1990–1997, and 1.5%/yr for 1998–2000, respectively. As a result, three rates of improvement were assumed after 2000: stationary (2000 level), 1.5%, and 3.0%. Because any sudden change in lifetime is unlikely in the future, average lifetime was set at 9 years if it shortens and 13 years if it lengthens, by assuming a ±2-year fluctuation in the current average lifetime of 11 years. Concerning the recovery rate of refrigerant, various rates between 0–60% were investigated.

3.3.2 Sensitivity analysis based on improvement of air conditioner performance

Fig. 8 shows the results obtained from a sensitivity analysis of GWP when keeping air conditioner lifetime at the present

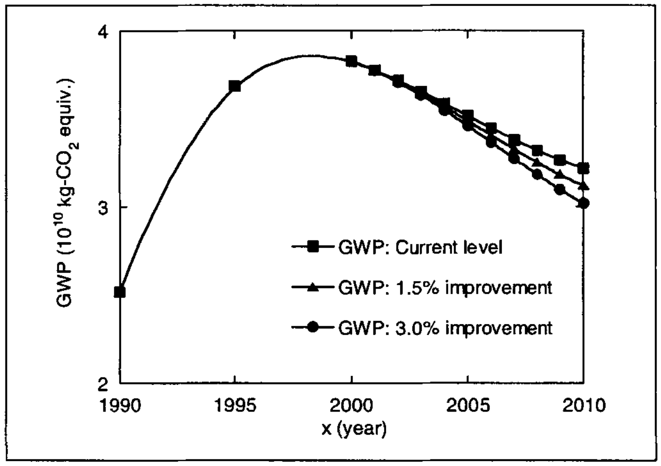

Fig. 8: Sensitivity analysis for performance improvement (actual level, 1.5% improvement and 3.0% improvement) in total GWP by all air conditioners in Japan during 1990–2010

11 years and changing the performance improvement rate. All cases exhibit a nearly straight decline, but there was little effect from performance improvement, because performance-caused differences among the three cases did not appear until 2005. When performance was the same as at present, GWP was 3.22×10^{10} kg CO_2 equiv. in 2010, or 27.7% higher than in 1990, but when performance improved at rates of 1.5% and 3.0%, GWP in 2010 was 23.8% and 19.8% higher than in 1990, respectively.

3.3.3 Sensitivity analysis based on change in average lifetime

Fig. 9 shows the results obtained from a sensitivity analysis of GWP when keeping air conditioner performance at the present 960 kWh/yr and changing lifetime.

When lifetime was shortened to 9 years, the total GWP was lower than for the present lifetime of 11 years until about 2005. the total GWP at first declined thanks to the appearance of new air conditioner models with better performance, but GWP then rose owing to the increase in the GWP caused by the disposal of retired units. On the other hand, a longer lifetime of 13 years did not help reducing energy con-

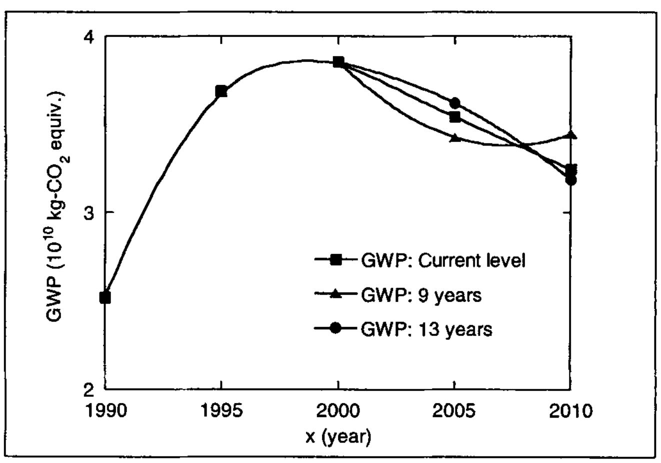

Fig. 9: Sensitivity analyses for lifetime change (11 ± 2 years) in GWP by all air conditioners in Japan during 1990–2010

sumption because fewer of the new high-performance models came into use, but disposal-stage GWP went down because fewer units were retired. Because those two factors canceled each other out, GWP changed little from the present level. Therefore, over the short term, the effect of average lifetime on the GWP of an air conditioner's population was to reduce the GWP through shorter product lifetime, while over the long term from 2010 and beyond, results suggest that shorter product lifetime would not necessarily be advantageous depending on the recovery of the refrigerant.

According to the results, total GWP in 2010 would be 36.6% and 26.5% higher than in 1990 for lifetimes of 9 and 13 years, respectively.

3.3.4 Sensitivity analysis based on refrigerant recovery rate

The foregoing results show that disposal-stage refrigerant management has a considerable influence on total GWP of the air conditioner population. For that reason, a sensitivity analysis of GWP was conducted with refrigerant recovery rates of 0%, 20%, and 50% (**Fig. 10**).

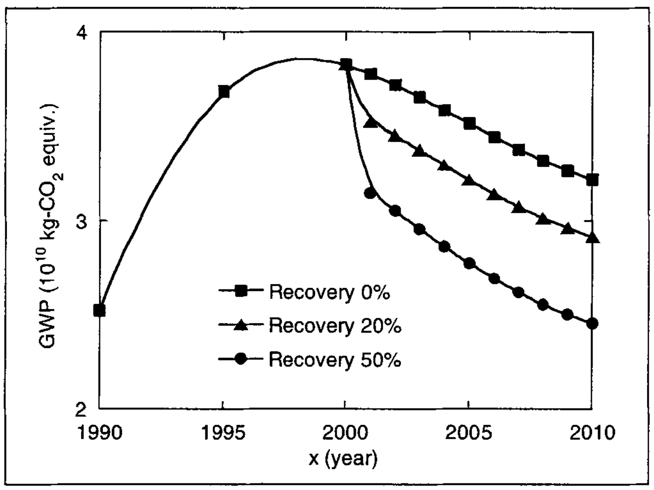

Fig. 10: Sensitivity analysis for refrigerant recovery rate (0%, 20% and 50%), as related to GWP, for all air conditioners in Japan during 1990–2010 under the stationary scenario

Under the stationary scenario, the analysis showed that the recovery rate would have to be at least 45.7%, to bring the GWP down to the 1990 level in 2010. If retired air conditioners are all taken to recycling plants and the refrigerant is properly recovered under the Appliance Recycling Law and other legislated requirements, it would then be possible to recover about 50%, which would very likely meet the COP3 target.

This examination of changes by using attainable ranges in performance, average lifetime and refrigerant recovery rates determined that the refrigerant recovery rate is the most effective factor for reducing GWP and complying with the COP3 target.

3.4 GWP Emissions under the steady growth scenario

Fig. 11 shows GWP under the steady growth scenario and a 0% refrigerant recovery rate.

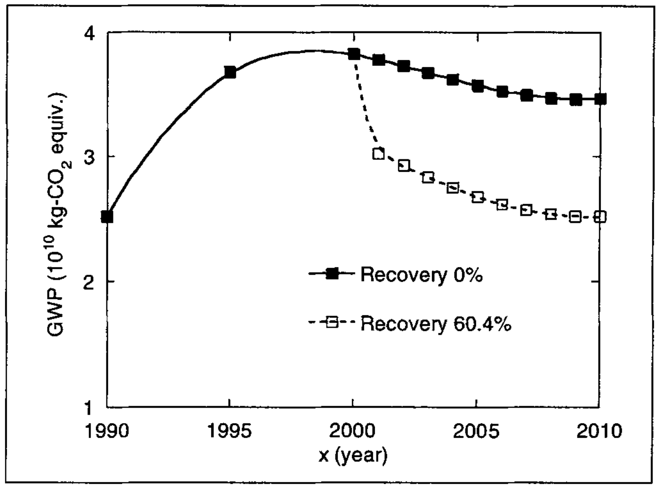

Fig. 11: Total GWP of all air conditioners in Japan during 1990–2010 according to steady growth scenario, at 0% and 60.4% recovery of refrigerant

The results indicate, although the number of air conditioners in use will grow by the addition of more units in use, that GWP will decline in 2000 and beyond. If the refrigerant from units added in 2000 and thereafter is not recovered, GWP in 2010 will be 3.47×10^{10} kg CO_2 equiv., a 37.8% increase over 1990 levels. But, assuming under this same scenario, that refrigerant is recovered to the extent needed for COP3 compliance, the recovery rate would have to be at least 60.4%. Thus, the results suggest that if the recovery rate of refrigerant from retired air conditioners is not improved, the COP3 target cannot be attained.

4 Conclusion

A PBM was used to analyze the change over time in the number of air conditioners in use, and integrated with LCA to quantitatively evaluate the GWP of the air conditioner population. Furthermore, scenarios were prepared on how the number of units in use would change. Estimated was the extent of improvement needed in the disposal-stage refrigerant recovery rate to comply with COP3 requirements under each scenario. These results showed how to proceed in reducing the GWP of air conditioners in Japan and how to produce targets for some parameters. The PBM-LCA method explored here offers a useful approach for quantifying the GWP in East Asia and Western countries, where the penetration of air conditioners is expected to increase. The same method is likely to be applicable not only to residential air conditioners, but also to refrigerators, which likewise create a sizeable GWP during disposal-stage refrigerant management, and to passenger cars with air conditioners, whose fleet in Japan is estimated to number at least 50 million [23]. In addition, not only GWP but also other environmental impacts by the product population can be investigated with this model if full-scale LCA results can be obtained. Dynamic numeric analyses using LCA integrated with PBM make it possible to conduct quantitative analyses of the environmental impacts caused by a variety of product populations and, by extension, they can be used in forecasts.

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Received: August 30th, 2002
Accepted: April 24th, 2003
OnlineFirst: April 25th, 2003

Appendix

Validity of the simplified model based on air conditioners with a 2.8-kW cooling capacity

The analysis using the model in this study has assessed environmental impacts over the entire life cycle under the assumption that all air conditioners in use have the same capacity of 2.8 kW, while in fact there is a great variety in their capacities (outputs). Therefore, the model to realistically account for the appliances in each capacity group (2.2, 2.5, 2.8 and 4.0 kW types) was redesigned. The GWP from the air conditioner population in each year was calculated with this model to check for agreement with calculations by treating the 2.8-kW class as a representative.

Since there are few statistical data available about the production ratios of each capacity group, we estimated the share of each capacity group in the total production, based on the number of different product models listed in the catalogues of home appliance companies in each year. This method was adopted in the previous case study [9] and reflects the demand of consumers. We collected data on the seasonal cooling/heating electricity consumption of air conditioner capacity classes from 2.2 to 4.0 kW. Assuming no change in parameters other than seasonal cooling/heating electricity consumption, GWP from the air conditioner population in each year was calculated under the stationary scenario. The results were shown in **Fig. 12**.

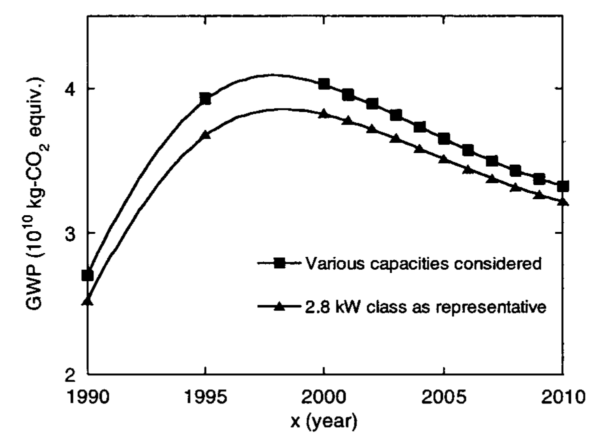

Fig. 12: GWP of all air conditioners in Japan during 1990–2010 considering various capacities, as compared with the representative 2.8-kW case

Despite an 8.0% difference in emissions from the 2.8-kW curve, the results coincide fairly well. This confirmation shows that the GWP quantification using the population of 2.8-kW units is more or less representative of all the air conditioners of various capacities.

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